AsterAnts: A Concept for Large-Scale Meteoroid Return and Processing using the International Space Station

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Abstract

AsterAnts is a concept calling for a fleet of solar sail powered spacecraft to retrieve large numbers of small (1/2-1 meter diameter) Near Earth Objects (NEOs) for orbital processing. AsterAnts could use the International Space Station (ISS) for NEO processing, solar sail construction, and to test NEO capture hardware. Solar sails constructed on orbit are expected to have substantially better performance than their ground built counterparts [Wright 1992]. Furthermore, solar sails may be used to hold geosynchronous communication satellites out-of-plane [Forward 1981] increasing the total number of slots by at least a factor of three, potentially generating $2 billion worth of orbital real estate over North America alone. NEOs are believed to contain large quantities of water, carbon, other life-support materials and metals. Thus, with proper processing, NEO materials could in principle be used to resupply the ISS, produce rocket propellant, manufacture tools, and build additional ISS working space.

Unlike proposals requiring massive facilities, such as lunar bases, before returning any extraterrestrial materials, AsterAnts could conceivably begin operation with a single spacecraft whose payload is no larger than a typical inter-planetary mission. Furthermore, AsterAnts could be scaled up to deliver large amounts of material by building many copies of the same spacecraft, thereby achieving manufacturing economies of scale. Because AsterAnts would capture NEOs whole, NEO composition details, which are generally poorly characterized, are relatively unimportant and no complex extraction equipment is necessary. In combination with a materials processing facility at the ISS, AsterAnts might inaugurate an era of large-scale orbital construction using extraterrestrial materials.

Near-Earth Meteoroids

Meteoroids are defined to be solid objects in space with diameters between 100 microns and 10 meters [Beech 1995]. We focus on the return to Low Earth Orbit (LEO) of meteoroids with diameters between 1/2 and 1 meter presently in orbits similar to that of the Earth around the Sun. Such meteoroids might be captured by relatively small spacecraft. Such NEOs should have a mass roughly equal to the dry mass of the Deep Space 1 and NEAR spacecraft (very roughly, 500 kg). Thus, they may be returned by current or near term propulsion systems such as solar electric. Capturing whole meteoroids and returning them may be simpler than returning part of a larger asteroid. Developing an automatic system to capture a meteoroid whole should be substantially easier than digging up a sample from a surface of unknown composition. For safety reasons, asteroids with diameters greater than about three meters should not be returned to LEO [Globus 1998].

There have been no direct measurements of the number of 1/2-1 meter diameter NEOs. However, approximately seven such objects enter the Earth's atmosphere each day [Ceplecha 1988] assuming densities similar to those calculated for asteroids. [Rabinowitz 97] estimates that there are approximately one billion ten-meter-diameter NEOs and there should be far more smaller objects. The distribution of NEOs with diameters greater than 10 meters roughly fits an inverse diameter power law with a coefficient of about 2.5. Finally, a substantial fraction of NEOs may be returned with lower round trip delta-v requirements than a round trip to the surface of the Moon (9.4 km/seconds) [Davis 1993]. (Delta-v is the change in velocity needed to move from one orbit to another). It is clear that the number of accessible objects in the desired size range is huge. Launch opportunities may be nearly continuous, although detection would be difficult. The detection problem is discussed below when we consider Earth-based telescopes for detection and radar for orbit/size/rotation characterization.

Not only are small NEOs numerous, they almost certainly have a very diverse composition. Laboratory studies of meteorite composition and the spectra of NEOs do not provide a consistent picture of NEO composition. Meteorite data reflect the internal composition of NEOs that survive atmospheric entry, while the spectra provide data on surfaces exposed to sunlight and deep space for millions of years. However, both measures strongly suggest that NEOs contain a wide variety of materials which probably include water, volatiles, and metals in large quantities [Nelson 1993], [Lewis 1993], and [Nichols 1993].

Solar Sails

Solar sails are a promising propulsion system for returning meteoroids because no reaction mass is necessary. (Reaction mass is the material thrown backward by a chemical rocket or solar electric propulsion system to generate forward thrust, taking advantage of Newton's third law). Thus, if the mass of a captured meteoroid has been underestimated, a solar sail could still return the meteoroid given sufficient time, whereas a reaction mass dependent propulsion system may become stranded in an orbit far from Earth. Solar sails are large sheets of thin reflective material that reflect photons to produce thrust. In the mid-1970s JPL designed, but never built or tested, a 820x820 meter solar sail to rendezvous with Halley's Comet [Wright 1992]. ([Wright 1992] provides the data for most of the following discussion). Solar sailing was also used by the

Mariner 10 mission to Mercury. This was done by differentially twisting the solar panels so solar pressure would create torque around the spacecraft's roll axis for attitude control.
The JPL study determined that an unloaded characteristic acceleration of approximately 1-2 mm/s^2 was probably achievable using 1970s materials. Much lower mass sails could be constructed in orbit [Drexler 1979]. (The characteristic acceleration is the acceleration of a sail directly facing the Sun at a distance of one astronomical unit (AU)). Actual acceleration is less because the sail must be oriented at an angle to the Sun to produce thrust in most directions. Thrust is generated approximately normal to the sail in the leeward direction. While 1-2 mm/s^2 may seem small, it is continuous. Given a characteristic acceleration of 1 mm/s^2, a solar sail produces a delta-v of approximately 1.3 km/s per month with the sail set at a 45 degree angle to the Sun. Such a sail could reach a large fraction of all NEOs within one year. Table 1 contains the size of square sails necessary to return a 500 kg meteoroid with two different desired characteristic accelerations and two different sail masses per unit area. Even with a very low characteristic acceleration, the sails need to be nearly 200 meters on a side. Although space manufacture does not reduce the size of sails much, the unloaded outbound leg would be much faster with the high-performance space manufactured sail because the sail itself has much less mass.

Table 1: The size of square solar sails necessary to achieve a particular characteristic acceleration when moving a 500 kg meteoroid. Data are given for two potential values for sail mass per unit area taken from [Wright 1992].

sail mass per unit area: g/m^2	side length (m) to achieve desired characteristic acceleration (including payload) = 1 mm/s^2	side length (m) to achieve desired characteristic acceleration (including payload) = 0.25 mm/s^2
5.27 (ground manufacture)	562	182
1.17 (space manufacture)	360	170

It should be noted that solar sails cannot operate below about 1000 km since atmospheric drag exceeds the acceleration due to sunlight. Orbits between approximately 1000 km and 20,000 km are subject to high radiation [Wright 1992]. Thus, solar sails built at the ISS would probably need to be moved to a 1,000+ km orbit by chemical, tether, or solar electric propulsion or construction must take place in a 20,000+ km orbit. Worse, aerodynamic pressure on large sails may pose a hazard to the ISS. Detailed engineering would be required to choose a proper site for sail construction, but a design where spars and rigging are assembled at the ISS then moved along with rolled sail material to a teleoperated facility in high orbit for final assembly may be advantageous.

Geosynchronous Applications

Admittedly, the financial return of delivering thousands of meteoroids to low earth orbit is a long-term prospect, making the development of the key technology, solar sails, a tough sell on that basis alone. However, solar sails could probably be employed to increase the number of geosynchronous satellite orbital slots by a factor of three, providing a compelling case for solar sail development in the short-term. Geosynchronous communication satellites are a thriving business generating substantial profits today. Geosynchronous satellites must be spaced approximately 2-3 degrees apart to avoid radio interference. Thus, only 120-180 satellites may be accommodated for a particular frequency band. This has led to substantial congestion, particularly in desirable locations. The last geosynchronous slot with a view of all of North America, a particularly crowded area, allocated for direct broadcast satellites was auctioned for in excess of $800 million. There are at least eight slots with a view of all of North America. A sufficiently capable solar sail could hold a geosynchronous communication satellite out-of-plane [Forward 1981]. Unfortunately, space manufactured sails are probably required to achieve 2-3 degree separation [Forward 1981]. However, solar sails might increase the number of geosynchronous slots with a view of North America by at least a factor of two. Assuming $250 million per slot [Van Bloom 1999], solar sails might create approximately $2 billion worth of North American direct broadcast slots alone, not including slots created south of the equator or over Eurasia, Africa, or Australia.

First Steps

In this section, we describe some of the steps that could be taken in the next few years to make AsterAnts a reality. Ground facilities could be used to develop computational models of solar sailing, meteorite processing, and orbital operations. A ground based telescope facility could be developed to detect and characterize 1/2-1 meter diameter NEOs. An orbital mission to demonstrate solar sailing should be fairly inexpensive. Finally, meteorites could be used to test meteoroid processing techniques on the ISS, small scale experiments to develop ISS techniques for thin aluminum film development could be started, solar sail assembly techniques could be developed, and meteorite capture experiments could be conducted with "artificial meteoroids" released from the ISS.

Ground Facilities

Computational Problem Solving Environment

Many detailed questions regarding AsterAnts development could be answered by a sufficiently well developed computational facility. Solar sail performance, navigation, optimal trajectory determination, and autonomous operations could all be investigated using simulation. Orbital materials processing might also be investigated using computational chemistry and materials techniques. While such investigations would require substantial computational resources, their cost is so much lower than orbital operations that only a few orbital improvements are necessary to justify the computational cost. The NAS facility at NASA Ames Research Center is developing the Information Power Grid (IPG) to provide large distributed computational resources for solving aerospace problems. A Problem Solving Environment using IPG resources could be developed to address AsterAnts development problems.

Ground Based Telescope Facility

Recognition that NEO impacts have played a very destructive role in Earth's history [Lewis 1996], highlighted by the spectacular collision of Comet Shoemaker-Levy with Jupiter, has spurred development of several successful NEO search programs. These include the Planet

Crossing Asteroid Survey [Helin 1979][Helin 1985], Spacewatch [Gehrels 1991], and the Near-Earth Asteroid Tracking program [Helin 1997]. Spacewatch alone had discovered 189 NEOs as of February 1999. These systems are designed to find NEOs somewhat larger than those that AsterAnts targets. For example, Spacewatch is most efficient at detecting asteroids with a diameter of approximately 300 meters [McMillan 1999]. One of the smallest NEOs ever discovered (1991 BA), with a diameter of approximately 5-10 meters, was discovered when only 0.0053 AU from the Earth. 1991 BA was discovered by the 0.91 meter Spacewatch Telescope [Scotti 1991]. An optical telescope capable of reliably detecting 1/2-1 meter diameter objects would probably require substantially greater light gathering capability and therefore be quite a bit larger, perhaps six meters diameter or greater. Six such telescopes currently exist.

Although optical telescopes do a good job of finding NEOs, radar is orders of magnitude more accurate for position determination [Ostro 1997] and can determine the size, shape, and rotation of NEOs. Radar telescopes cannot find unknown NEOs because their beam is narrow, so a facility to find and characterize one-meter-diameter meteoroids accurately would require both an optical and a radar telescope. Extrapolating from table 2 in [Ostro 1997], existing radar facilities could image one-meter-diameter meteoroids out to a distance of 0.006-0.018 AU. For comparison, the Moon is approximately 0.0026 AU from Earth. [Ostro 1997] proposes a dedicated radar telescope for NEO imaging. This facility is proposed to characterize large NEOs that threatened Earth. Presumably, only minor adjustments would be necessary for such a facility to be part of an AsterAnts ground infrastructure.

The search for appropriate meteoroids should begin at least a few years before AsterAnts spacecraft become available. This should provide numerous targets when the spacecraft are ready. If AsterAnts does not pan out, the telescope facility would be useful for a wide variety of scientific observations and for detecting Earth threatening NEOs.

Solar Sail Demonstration

In the 1980s, the World Space Foundation developed a solar sail engineering test article and demonstrated deployment on the ground. Development was halted when no affordable launch opportunity could be found. This development was accomplished without government funds, only voluntary contributions. Given the relative success of a shoe-string operation, a modestly funded effort could be reasonably expected to build, launch, and operate an orbital solar sail mission. The major risk is deployment failure. A series of small ground built solar sails might be used to develop an experience base for AsterAnts solar sails.

ISS Experiments

Meteorite Processing

Meteoroid processing experiments need not wait for the return of meteoroids. Hundreds of meteorites have been collected on Earth and some of these could be used to develop on-orbit processing facilities. Meteorites represent that subset of meteoroids that collide with Earth and survive atmospheric entry. Therefore, there is no guarantee that the first meteoroids returned by AsterAnts would be similar to the meteorites used to develop on-orbit processing. However, if a sufficiently large number of meteoroids are returned by AsterAnts, some would undoubtedly have characteristics similar to meteorites in existing collections. Full-scale meteoroid processing is expected to be very energy intensive, possibly requiring a solar furnace. However, initial experiments should be possible with projected ISS energy supplies.

Solar Sail Construction

Although full-size solar sails would probably be built only in high orbits, small sails could be built at the ISS to develop construction techniques. Spars and rigging compressed into small packages could be brought to the ISS by the shuttle and assembled on orbit. Rolls of ground-built sail material could also be delivered along with machinery to unroll the sail material onto the spars and rigging. A human presence would be of great value in understanding and fixing deployment and construction problems. Once the procedures have been thoroughly debugged, the facility could be moved to high orbit for full-size sail construction.

Solar Sail Materials Manufacturing

To build solar sails on-orbit, tens of thousands of square meters of thin-film aluminum must be produced. Clearly, this would require a large, dedicated facility outside of the pressurized ISS volume. However, experiments to understand the behavior of thin-films in weightlessness and to develop manufacturing techniques could be conducted in the pressurized volume. For sail making, one approach is an electroplating technique, where a large drum is continuously plated with evaporated, charged aluminum on one side, and the solidified sheet is peeled off the back side of the roller. A more elaborate mechanism, credited to Eric Drexler, appears in [Wright 1992].

"Artificial Meteoroid" Capture

A critical portion of each AsterAnts return mission is meteoroid capture and control. These operations could be tested at the ISS by developing a controllable "artificial meteoroid" that mimics the characteristics of the real thing to test the capture and control hardware and software. A human presence would allow a much quicker try-and-fix cycle.

Conclusion

The AsterAnts concept uses the ISS to help develop a fleet of small spacecraft, propelled by very large solar sails, to capture and return meteoroids from near Earth orbits. These meteoroids could be used for ISS resupply, hydrogen/oxygen propellant production from water, and metals for orbital construction. While the overall project is large, a number of small steps could be taken in the near future that have near-term value while contributing to the long-term goal. Although developing solar sails, meteoroid capture hardware, and meteoroid processing is probably too risky for the private sector, once the technologies have been demonstrated and one or two meteoroids returned, it may be possible for the government simply to pay for meteoroids delivered to the ISS by the kilogram, with a price conceivably competitive with materials boosted from Earth. This would provide a market for private companies to develop fleets of AsterAnts providing extraterrestrial materials for the massive expansion of human activities in space.

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